B physics with the Dzero Detector Upgrade
DØ note 3677

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The DØ detector has been undergoing a major upgrade in preparation for the high luminosity run at the Tevatron. This document reviews the components of the upgrade with an emphasis on the new B physics capabilities. Projections for the observability of the CP violation are made based on the upgrade simulation. It is shown that measurement of $\sin 2\beta$ can be achieved at DØ with uncertainty below 0.1 for an integrated luminosity of 2 fb^{-1}.

1 Motivations for the Upgrade

The next run of the Tevatron in collider mode is scheduled to begin in summer of 2000 with a major upgrade of the accelerator. The design goal to deliver 2fb^{-1} of $p\bar{p}$ collisions in about two years of running with an instantaneous luminosity of 2×10^{32}cm^{-2}s^{-1}. An increase from 1.8 TeV to 2.0 TeV of the collision energy is also planned, representing a 40% enhancement in $t\bar{t}$ yields.
The upgrade of the DØ detector is driven both by the changes in the collider operating characteristics and by new physics goals.

1.1 Collider upgrade

The collider upgrade[1] is based on the replacement of the Main Ring, the last pre-acceleration stage originally used for the run I, by the Main Injector. Located in a tunnel separate from that of the Tevatron, the Main injector is a new 120-150 GeV/c rapid proton synchrotron machine which improves significantly the $\bar{p}$-production capability. Coupled with upgrades in the $\bar{p}$-cooling and stacking, it permits re-use of those $\bar{p}$ remaining in the Tevatron at the end of a store. This results in a factor 2 enhancement in the number of $\bar{p}$ available for collisions, and a factor 10 enhancement in the delivered luminosity with respect to run Ib performance. This has a significant impact on the detector imposing the use of radiation hard subdetectors.

The number of $p \times \bar{p}$ bunches circulating in the Tevatron is also increased, from 6×6 for run Ib to 36×36 and eventually 108×108 for run II. Consequently, the spacing between bunch crossing is decreased from 3.5 μs to 396 ns and eventually 132 ns, in order to keep the number of interactions per crossing between 1-2. This decreased bunch spacing forces the replacement of all the front end electronic systems of the detector to introduce pipelines.

1.2 Physics goals

Physics motivations are driven by the needs to control systematics biases in high precision measurement of W and top masses, as well as in direct searches for Higgs and B-physics analyses. In all of these areas, high performance lepton ID, track reconstruction and B-tagging capabilities are crucial. The upgraded DØ detector improves its capabilities in each of these fields.

At the Tevatron, the $b\bar{b}$ production cross-section is 100 μb, corresponding to 20 Hz of $b\bar{b}$ events at $\mathcal{L} = 2 \times 10^{32} cm^{-2} s{-}1$. However, contrary to electron machines, sample purity in a hadron collider environment is about $\sigma_{\mathrm{b\bar{b}}}/\sigma_{\mathrm{p\bar{p}}} \approx 1/1,000$. Therefore good background rejection at the trigger level is of vital importance. Specific algorithms devoted to B detection have been developed and included in a new DØ trigger architecture. A Level-1 (L1) trigger includes pipeline and permits the use of crude combinations of detector specific information; a Level-2 (L2) allows refined information to be correlated, including vertex information; a Level-3 (L3) takes a decision upon reconstructed events. B triggers are based on the detection of soft leptons coming from semi-leptonic b-decays or from J/Ψ's, along with high impact parameter tracks from B vertex.

2 The DØ detector Upgrade

A detailed description of the DØ detector may be found elsewhere [2]. The upgraded apparatus is displayed in Fig 1 and comprises a new tracking system, inserted inside a 2T solenoid magnet, new pre-shower detectors, as well as significant additions to the muon system. The calorimeter remains unchanged, except for a complete revision of its front end electronics [3]. All electronic systems, DAQ and triggering architecture are also being redesigned for run II.

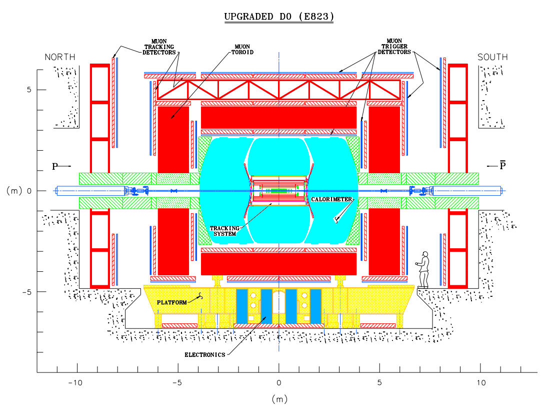

Figure 1: *The upgraded DØ detector.*

2.1 The Tracking detectors

The upgraded tracking system consists of a silicon strips vertex detector and a scintillating fiber tracker inside a 2T solenoid magnet, as shown in Fig 2.

Silicon Microstrip Tracker (SMT)

The SMT [4] is designed to accomodate for the large luminous region ($\pm$25cm) expected for the run II. It consists of silicon strip disks and barrels, formed into six disk/barrel modules covering $|z| < 32$ cm, and a set of forward disks located from $z = \pm 45$ cm to ± 126 cm.
Each barrel module consists of four radial layers of detector ladder assemblies mounted on baryllium support structures with radius of 2.7, 4.5, 6.6 and 9.5 cm. Layers one and three are single sided silicon microstrip detectors, and layers two and four are double sided with 2^o stereo angle. Each disk module has 12 wedge-shaped double sided detectors with a 30^o stereo angle and extends radially from 2.7 to 10 cm. Six forward disks of similar design are located between ± 45 cm and ± 55 cm in z. At the very forward region, four larger disks of single sided detectors help improve track reconstruction and momentum resolution up to $|\eta| = 3$ in rapidity.

The readout is based on the use of SVX-II chips [5] (on board). At this stage signals are processed for triggering and digitized [6] at a rate of 53 MHz. A total of about 793,000 channels is read out and used by the Level 2 triggers.

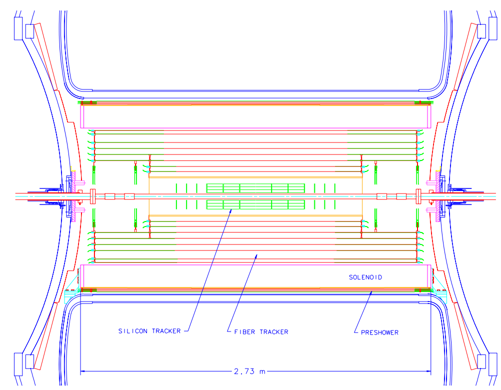

Figure 2: *The new DØ tracking system.*

Central Fiber Tracker (CFT)

The CFT [7] consists of scintillating fibers mounted on eight concentric carbon fiber cylinders, covering the rapidity region between $|\eta| < 1.6$. The fibers are double clad and are 835 microns in diameter. They are assembled in ribbons each 128 fibers wide, composed of doublets. Each cylinder contains an axila and a 3^o helical stereo fiber doublet.

The light from the fibers is converted into electrical pulses by Visible Light Photon Counters (VLPC). These are silicon devices with eight photosensitive areas, each 1 mm in diameter on their surface. When operated at temperatures about 10 K, they have a quantum efficiency of over 80%

and a gain of about 50,000.

The detector readout is divided into 80 azimuthal sectors. Each sector has 896 fibers and the entire detector has 71,680 channels. The axial fibers are used to form a fast Level 1 hardware trigger. All fibers are read out on a Level 1 trigger accept and are used for a Level 2 trigger. Digization is performed by a SVX-II.

Tracking Performance

The performance on the momentum resolution is displayed for single muons in Fig. 3 as a function of the p_T of the track. A resolution of $\sigma_p/p_T^2 \approx 0.002$ (combination of SMT+CFT) is obtained for low p_T when using both the CFT and the SMT detectors.
Tracks are reconstructed with high efficiency in the central region ($|\eta| < 1.6$), while the forward disks provide the ability to reconstruct tracks up to $|\eta = 3$.
The accuracy with which the vertices are reconstructed depends on the event occupancy. For the primary vertex, a resolution of 15 μm (30 μm) in $r - \varphi$ is expected for $t\bar{t}$ ($b\bar{b}$). For secondary vertices, resolution of 40 μm in $r - \varphi$ and 100 μm in $r - z$ is expected.

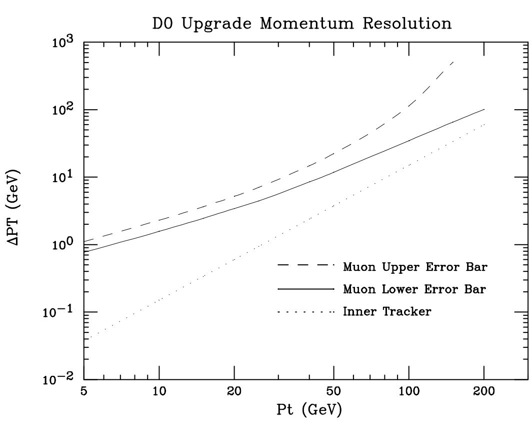

Figure 3: *Uncertainties on muon p_T as function of p_T.*

2.2 Pre-Shower detectors

Pre-Shower detectors are mounted on the inner calorimeter cryostats, and are designed to enhance electron identification. Composed of nested triangular scintillator strips, they provide particle discrimination by exploiting the difference electron/photon and hadron showers.

Forward Pre-Shower (FPS)

Each FPS detector[8], covering $1.5 < |\eta| < 2.5$, consists of four layers of scintillating strips composed of sixteen 22.5^o modules in φ. Each module consists of two layers of (7 mm base and 5 mm high) nested triangular strips, forming a stereo angle of 22.5^o with respect to one another. A 2 X_o lead sheet separates two small modules from larger modules used to measure the shower energy. The signal is read out from the edge of the detector through clear transmission fibers routed to VLPC's. All strips are used for Level 1 and Level 2 triggers.

Central Pre-Shower (CPS)

The CPS detector [9] is a 2.6 m long cylinder surrounding the solenoid magnet. It consists in three layers of scintillating strips, identical to those used in the forward detector. The layers provide $r - \varphi$ and $\pm 11^o$ stereo coordinates. The readout of the inner layer is arranged to match the CFT trigger segmentation, providing fine spatial match at the Level 1 hardware trigger level. Stereo fibers are readout independantly for Level 2 use.

2.3 The Muon detectors

Central Muon Detector

The Central Muon system [10] covers the rapidity region $|\eta| < 1$, and consists of a toroid magnet and two detectors systems: a set of large drift chambers constructed from extruded aluminium proportional drift tubes (PDTs), and cosmic ray counters constructed from scintillator and wavelength shifting fibers.
The run I PDT planes are retained, with a faster gas ($Ar + CH_4 + CF_4$) used to decrease the drift time to about 4 crossings for 132 ns bunch spacing.
Underneath the toroid magnet, a new scintillator layer of 132 scintillator counters is added to the already existing scintillator plane covering the top

and the sides of the central drift chambers. In addition a scintillation counter layer is mounted between the calorimeter and the toroid magnet, providing a tag for low p_T-muons, and improved spatial match with the fiber tracker at the hardware trigger level.

Forward Muon Detector

The Forward detector [11,12] ($1 < |\eta| < 2$) consists of Mini Drift Tubes drift chambers (MDTs) for muon track reconstruction, and of layers of scintillation counters for triggering. Three layers of high granularity MDTs replace the old PDTs planes and provide muon momentum measurement with an accuracy of $\sigma_p/p = 20\%$ limited by multiple scattering toroids for low momentum muon, as well as a coordinate resolution below 1 mm. Three planes of scintillation counters are introduced to extend triggering capabilities. Arranged in r-φ geometry to match the CFT trigger segmentation, the muon trigger combines tracks with muon hits up to $|\eta| < 1.6$. For $1.6 < |\eta| < 2$, MDTs are used to confirm trigger based on scintillation counters.

3 Trigger system Upgrade

The trigger architecture, rebuilt to accomodate for a reduced bunch spacing, is organized in three levels [13].

3.1 Level 1 trigger (L1)

The L1 trigger operates with no deadtime at a rate 7.6 MHz and a latency of less than 4.2 μs. The L1 trigger accept rate is less than around 10 kHz, limited by the rate capability of the SVX-II readout chip and calorimeter triggers logic. The L1 trigger is based on information extracted from four sub-detectors systems independently (CFT, preshowers, calorimeter and muon) combined in the L1 Framework. Each front end digitizing crate includes pipelines to retain data from 32 crossings without deadtime at 7 MHz. The L1 Framework (L1FWK) supports 128 pre-programmed combinations of detector specific triggers through series of Field Programmable Gate Arrays (FPGAs). The L1FWK determines if at least one these triggers is satisfied. Upon an accept decision, the event data is digitized and routed from the pipeline into Level 2 input buffers.

3.2 Level 2 trigger (L2)

The L2 trigger is based on the extensive use of fast serial and parallel processing. It is composed of a global L2 processor (L2GLB) that operates on a list of objects coming from detector-specific L2 pre-processors (L2PP) operating in parallel. Each sub-system L2PP retains L1 information and forms physical objects such as clusters (energy, location) and tracks in about 50 μs. The resulting list of objects is then passed to the L2GLB, where appropriate spatial and other (for example, p_T) matching between the objects found in the various detectors will take place. The L2GLB receives pre-processor information through links operating at 320 MBytes/s and is designed to make a decision within 75 μs with an output rate of 1 kHz. It should provide a factor $\times 10$ in rejection, with an amount of deadtime below 5%. A L2 Framework (L2FWK) utilizing the same FPGA logic as the L1FWK will report the decision to Level 3.
The relationships between L1 and L2 triggers are shown in Fig. 4.

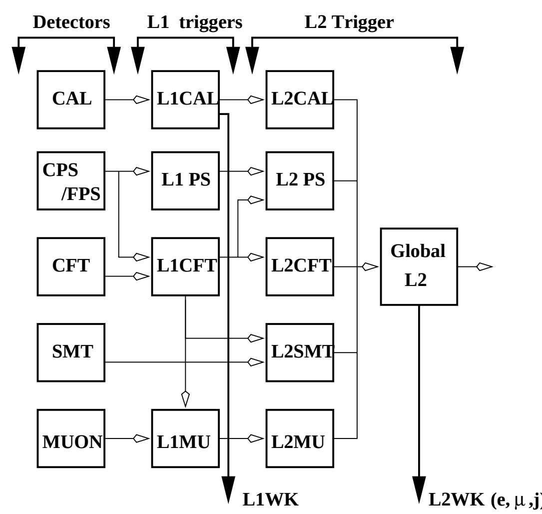

Figure 4: *L1 and L2 trigger elements. Horizontal arrows denote the information flow.*

3.3 Level 3 trigger (L3)

The L3 trigger system is a straightforward upgrade of the existing data acquisition and trigger. Upon a L2 accept from the L2GLB, the L3 initiates the move of digitized data into transfer buffers. Events are then transferred from the Front End crate to a farm of 48 processors, where they are examined through a suite of filters. The output rate is about 50 Hz for selected events.

4 B triggers with DØ

The B hadron observability depends strongly on the detector capabilities to trigger on soft lepton(s) present in semi-leptonic channel or in J/Ψ's produced in B decays. Hadronic B triggers are not considered in the following.

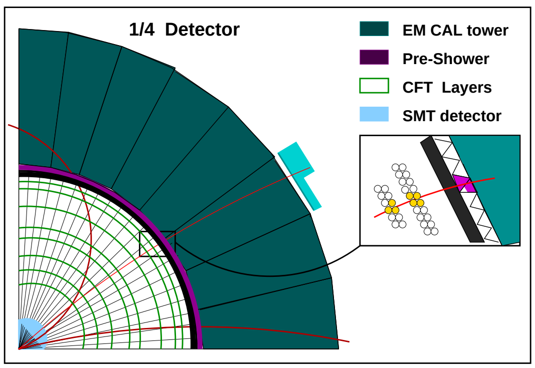

Figure 5: *Level 1 and Level 2 electron triggers.*

4.1 Soft lepton trigger

The L1 Muon hardware trigger is based on the combination of low p_T track candidates measured in the CFT, spatially matched with hits in the scintillator planes and/or drift chambers. Single muon events with $p_T^\mu > 4$ GeV/c or di-muons with $p_T^\mu > 2$ GeV/c are expected to run unprescaled in the central rapidity region.

The electron trigger is aimed at soft electron pair detection. L1 candidates are selected separately in EM calorimeter trigger towers ($\Delta\eta = \Delta\varphi = 0.2$) with a transverse energy deposit $E_T > 2.0$ GeV, and in the tracking system with low p_T (> 1.5 GeV/c) track coincident with pre-shower cluster. Electron candidates of both systems are then required to match within a quadrant in φ (see Fig 5) and to have opposite signs. Studies show that the combination at L1 of calorimeter and track/pre-shower information brings a factor 4-8 in background rejection with respect to a purely calorimeter-based trigger.

L2 triggers are based on a refined 2-dimensional spatial match between tracks and $\Delta\eta \times \Delta\varphi = 0.2 \times 0.2$ EM trigger towers. They also include the use of EM fraction and isolation criteria for electrons. Invariant mass window and angular cuts in di-lepton channels may also be set to select J/Ψ decays and improve background rejection (see Fig. 6).

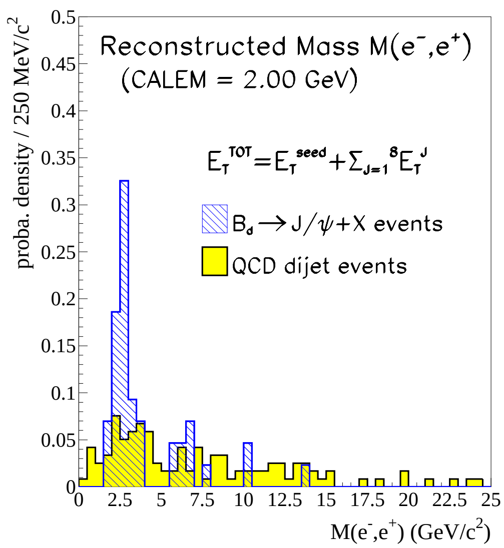

Figure 6: *Invariant Mass $M_{e^+e^-}$ at Level 2.*

4.2 Vertex trigger

Vertex information from the SMT is also used at L2. The SMT trigger projects L1 CFT tracks into the SMT volume, finds silicon hits in CFt tracks road and fits the SMT tracks using a linearized equation. It then computes the impact paramater significance (as well as vertex along z) used to select tracks coming from B vertex.

Requirements on impact parameter are shown to improve the rejection by a factor 10-25 with respect to L1 rates, depending on the significance cut. At the same time, more than 70% of the signal is preserved.

4.3 Projection for $\sin 2\beta$ measurement

Efficiencies and rates are estimated using *ISAJET* generated events, fully reconstructed through the GEANT simulation of the DØ detector. All these events are overlaid with 2 minimum bias interactions, in order to reproduce the running condition at $\mathcal{L} = 2 \times 10^{32} cm^{-2} s^{-1}$.

$B_d^0 \rightarrow J/\Psi(\rightarrow l^- l^+)\ K_s^0(\rightarrow \pi^+\pi^-)$ decays are selected with efficiencies of 30% for central muon and 20-25% for central electron. Rates are estimated to be below 1 kHz at L1 and 150 Hz at L2 for the combinaison of both channels. The yield for triggered $B_d^0 \rightarrow J/\Psi\ K_s^0$ events is estimated at 15,000 for $\mathcal{L} = 2\ fb^{-1}$.

The sensitivity to $\sin 2\beta$ depends on the flavour tagging efficiency ε_{tag}, the dilution factor D and the signal over background ration S/B. With a track reconstruction efficiency of 95 %, a flavour tagging of $\varepsilon_{tag} D^2 = 5\,\%$ [14] and a ratio $S/B = 1$, this translates into a statistical sensitivity on $\sin 2\beta$ of ± 0.1 using combined electron and muon channels.

5 Conclusion

With a new tracking and pre-showers detectors, improved muon system, and a complete revision of electronic and trigger systems, the DØ detector is undergoing a major upgrade. This results in a significantly enhanced B physics reach in run II, with, for example, 15,000 $B_d^0 \rightarrow J/\Psi\ K_s^0$ events for $\mathcal{L} = 2\ fb^{-1}$. A sensitivity of ± 0.1 on $\sin 2\beta$ measurement can be achieved.

6 Acknowledgements

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